

The Space Infrared Interferometric Telescope (SPIRIT): mission study results

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ABSTRACT

We report results of a recently-completed pre-Formulation Phase study of SPIRIT, a candidate NASA Origins Probe mission. SPIRIT is a spatial and spectral interferometer with an operating wavelength range 25 - 400 μ m. SPIRIT will provide sub-arcsecond resolution images and spectra with resolution $R = 3000$ in a 1 arcmin field of view to accomplish three primary scientific objectives: (1) Learn how planetary systems form from protostellar disks, and how they acquire their chemical organization; (2) Characterize the family of extrasolar planetary systems by imaging the structure in debris disks to understand how and where planets form, and why some planets are ice giants and others are rocky; and (3) Learn how high-redshift galaxies formed and merged to form the present-day population of galaxies. Observations with SPIRIT will be complementary to those of the James Webb Space Telescope and the ground-based Atacama Large Millimeter Array. All three observatories could be operational contemporaneously.

Keywords: infrared, submillimeter, interferometry, infrared detectors, cryogenic optics, Origins Probe

1. INTRODUCTION

In 2004 NASA solicited Origins Probe Mission Concept Study proposals and selected the Space Infrared Interferometric Telescope (SPIRIT) and eight other concepts for study. Previously SPIRIT had been recommended in the *Community Plan for Far-Infrared/Submillimeter Space Astronomy*¹ as a pathfinder to the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), which had been accepted into the NASA astrophysics roadmap following recommendations of the Decadal Report *Astronomy and Astrophysics in the New Millennium*.² While SPECS is conceived as a 1-kilometer maximum baseline far-IR interferometer requiring multiple spacecraft flying in a tethered formation,^{3, 4, 5} SPIRIT was

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intended by the infrared astronomical community as a less ambitious yet extremely capable mission, and a natural step in the direction of SPECS.

The IR astrophysics community recommended SPIRIT knowing that far-IR observatories providing visual acuity orders of magnitude better than that of the current and near-future telescopes will be needed to answer the compelling scientific questions that motivate NASA's Astrophysics Division and inspire young explorers: How do planetary systems form from the disks of material commonly found around young stars? Why do some planets end up being hospitable to life as we know it, while others do not? How did galaxies form and evolve, occasionally colliding, erupting with newborn stars, and emerging from their dusty cocoons with freshly-forged chemical elements? The magnificent data returned from the 85-cm diameter Spitzer Space Telescope hint at the progress that will be made when sharper infrared images can be obtained, but Spitzer's far-IR images are no clearer than those seen by Galileo with the most primitive astronomical telescope. SPIRIT will provide far-IR images a hundred times sharper than those of Spitzer, and SPECS, perhaps a decade later, will further improve the image quality by another order of magnitude.

We adopted a methodical approach to mission design. The SPIRIT Science Team developed a Design Reference Mission to capture the measurement capabilities needed to achieve a wide range of possible science objectives. To understand the dependence of scientific value on cost, and to assess the viability of SPIRIT as an Origins Probe mission, we specified measurement requirements for, engineered, and evaluated three mission design concepts. First the SPIRIT Engineering Team developed engineering designs for ambitious (A) and relatively modest (B) concepts, aiming to bracket the Origins Probe cost target, \$670M. After assimilating lessons from the A and B studies and evaluating science priorities, we chose a final set of measurement requirements and developed a third mission design (C). During the C design cycle, features of designs A and B were included or excluded according to their costs and benefits, and more thought was given to the technology development program, the Integration and Test program, and the spacecraft bus requirements. Thus, the C design is more mature than the A and B designs. Upon completion of the C design cycle and independent validation of the estimated C design cost, the design was reviewed by an external Advisory Review Panel.

SPIRIT Design C will enable us to accomplish the following scientific objectives: (1) Learn how planetary systems form from protostellar disks, and how they acquire their chemical organization; (2) Characterize the family of extrasolar planetary systems by imaging the structure in debris disks to understand how and where planets of different types form; and (3) Learn how high-redshift galaxies formed and merged to form the present-day population of galaxies. These are central goals in the science plan for NASA's Astrophysics Division and they relate directly to the Agency's quest to "conduct advanced telescope searches for Earth-like planets and habitable environments around other stars."

Only a space-based far-IR observatory can make the observations needed to achieve the scientific objectives listed above. Protostars, proto-planetary disks, planetary debris disks, and young galaxies radiate most of their energy at far-IR wavelengths. Visible and near-IR light is emitted less strongly, and severely attenuated by foreground dust. This obscuring material is ubiquitous in the places of interest because all stars and planets are born in dense, dust-laden molecular clouds. Far-IR light from these stellar and planetary nurseries can readily penetrate the dust and reach our telescopes. While longer-wavelength (millimeter and sub-millimeter) light also reaches Earth and, indeed, penetrates our atmosphere where it can be measured with ground-based telescopes, only the far-IR spectrum harbors the information necessary to answer the questions posed above. The Earth's atmosphere absorbs far-IR light, and high-altitude ambient-temperature telescopes are limited in sensitivity because the photons emitted by the telescope swamp those of interest from the sky. Thus SPIRIT, like the predecessor missions IRAS (Infrared Astronomical Satellite), COBE (Cosmic Background Explorer), ISO (Infrared Space Observatory), and Spitzer, will be a cryogenically cooled space-based observatory.

SPIRIT has two 1 m diameter light collecting telescopes and a Michelson beam combining instrument. The telescopes can be separated by distances ranging up to 36 m, and the optical delay line in the beam combiner can be scanned to provide, simultaneously, sub-arcsecond angular resolution images and $R = \lambda/\Delta\lambda = 3000$ spectral resolution. Cryo-cooled optics and sensitive detectors enable SPIRIT's sensitivity to be limited by photon noise from the sky.

Additional features of the SPIRIT C design are presented in this paper, which is organized as follows. The SPIRIT science goals and the measurements required to achieve them are detailed in Section 2. Section 3 describes the engineering implications of the measurement requirements and most of the important aspects of the C design.

Information about SPIRIT's unique capabilities relative to those of other current and planned facilities is given in Section 4, which is followed by a short summary in Section 5.

2. SCIENCE WITH SPIRIT

To facilitate mission planning the SPIRIT Science Team reviewed many potential scientific objectives for a far-IR spatial and spectral interferometer, prioritized the objectives, and developed a Design Reference Mission (DRM). The DRM outlines the measurement capabilities (number of targets, wavelength range, field of view, angular and spectral resolution, sensitivity, and dynamic range) required to achieve all of the considered potential objectives. This enables us to measure the extent to which alternative mission design concepts satisfy the measurement requirements. Only the measurement requirements corresponding to the three scientific objectives classified as "primary objectives" were allowed to drive the mission design.

In Section 2.1 we describe the three primary objectives of the SPIRIT mission. Additional possible applications for the observatory are listed in Section 2.2. In Section 2.3 the measurement capabilities of SPIRIT are compared with those of current and near-future far-IR observatories, and with two facilities whose observations will be complementary to those of SPIRIT: the James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA).

2.1. Primary scientific objectives

The SPIRIT Science Team prioritized science objectives according to their perceived importance to advancing astrophysical knowledge, their relevance to the higher-level science objectives of NASA's Astrophysics Division, the plausibility that a cost-constrained far-IR mission like SPIRIT could make the required measurements, and the extent to which *only* SPIRIT could make the necessary measurements. Three objectives were considered by the SPIRIT Science Team to satisfy these criteria, and were adopted as "primary scientific objectives" for the mission: with SPIRIT we will: (1) learn how planetary systems form from protostellar disks, and how they acquire their chemical organization; (2) characterize the family of extrasolar planetary systems by imaging the structure in debris disks to understand how and where planets of different types form; and (3) learn how high-redshift galaxies formed and merged to form the present-day population of galaxies. These goals are clearly traceable to NASA's strategic objectives to (a) "conduct advanced telescope searches for Earth-like planets and habitable environments around other stars"; and (b) "explore the universe to understand its origin, structure, evolution, and destiny."

The prioritized objectives for the SPIRIT mission will be recognized as compelling by young explorers and the general public, and SPIRIT will likely uncover unimaginably beautiful scenes whose aesthetic value alone will be a source of inspiration. Thus, SPIRIT will also satisfy the NASA strategic objective "to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation."

Below we summarize each of the primary objectives and explain how SPIRIT will be used to achieve them.

2.1.1. Goal 1: Learn how planetary systems form

The greatest obstacle to our understanding how planetary systems form is the lack of an observing tool that can decisively constrain theoretical models. Two factors have allowed theorists to speculate almost freely. First, planets form in dusty environments, so protoplanetary disks are generally impossible to see at visible wavelengths. Hubble Space Telescope (HST) images of the proplyds in Orion⁶ tantalize us for this reason. Second, the far-infrared light from protoplanetary disks, which is their dominant emission, has only been seen as an unresolved blur or, worse, as the blended emission of many objects in a single telescope resolution element. To break model degeneracy and learn how planetary systems form it is essential to obtain spatially-resolved far-IR observations of protostars and protoplanetary disks. At the distance of the nearest concentration of objects thought to be forming planets, 140 pc, angular resolution of about 0.1 arcsec will be needed to resolve the structures of interest. The Spitzer Space Telescope and the planned far-IR observatories Herschel and SOFIA (the Stratospheric Observatory for Infrared Astronomy) lack the necessary resolution by more than an order of magnitude.

To gain astrophysical insight we will need more than a single high-resolution broadband image. The far-IR continuum will be dominated by thermal emission from dust, but the shape of the spectral energy distribution (SED) will depend on several coupled factors: the dust temperature, grain size distribution, dust grain optical properties, the three-dimensional density distribution, and radiative transfer. Hence, model degeneracy will remain unless the SED is measured at many positions.

Although observations of the dust emission will allow us to probe the physical conditions at various locations in protoplanetary disks, dust is a minor constituent of the interstellar medium by mass. Direct measurements of the molecular hydrogen gas will also be needed to determine if and when the disks surrounding young stars attain the density distributions characteristic of hydrostatic equilibrium.^{7,8} Surrogate tracers of the dominant H₂ molecules, such as CO line emission, can be observed, but photodissociation, freeze-out onto grain surfaces and uncertain excitation conditions complicate the interpretation of such indirect probes of gas density. The readily excited H₂ spectral lines at 28 and 17 μm are the best probes of gas density, and both lines should be observed to calibrate the effects of varying excitation conditions. Variations in the H₂ line excitation temperature are expected to exist both spatially around a single star, and from object to object.

Finally, we will want to understand when and how chemical differentiation occurs in protoplanetary disks. The H₂O molecule has a rich far-IR spectrum, and the solar system teaches us that water is not evenly distributed among the planets. Given the importance of water in biological systems, and our keen interest in habitable environments, the relevance of these uniquely far-IR measurements is self-evident. The far-IR spectrum also contains strong C and O fine structure lines, which can be used to measure the C/O ratio. That abundance ratio is thought to affect the composition, surface chemistry, and perhaps the habitability of planets.⁹

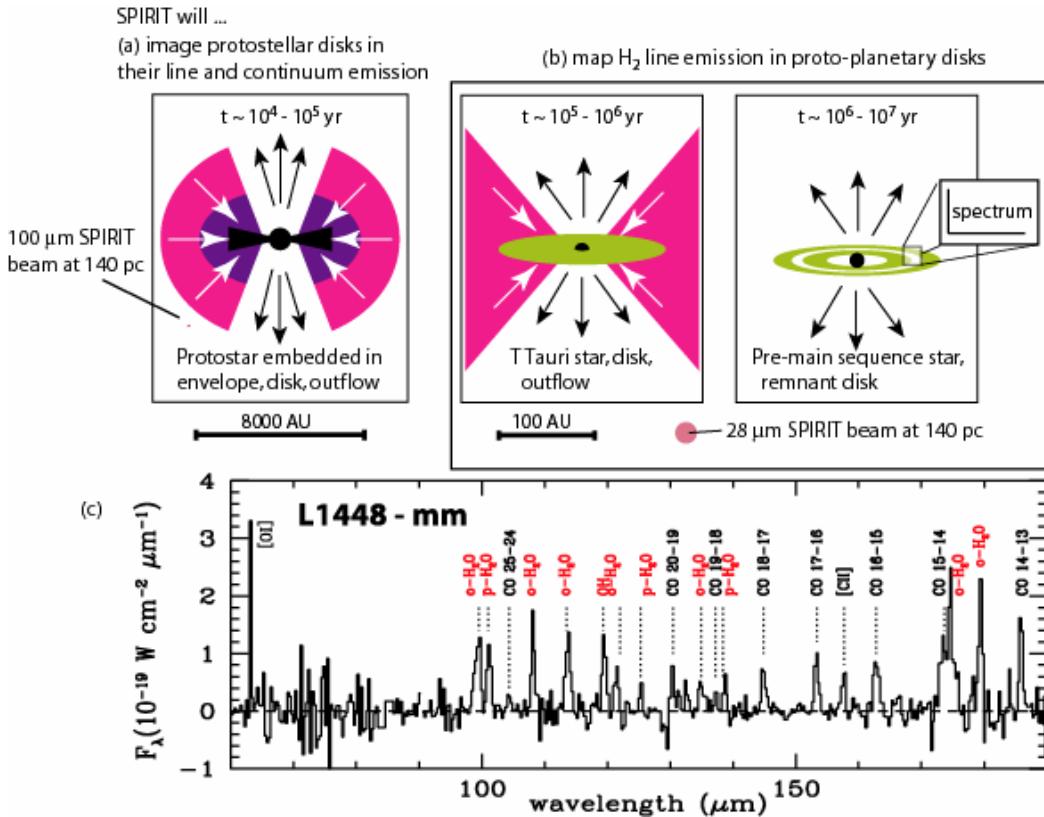


Figure 1 – SPIRIT, which naturally produces spatial-spectral “data cubes,” will (a) image protostellar disks in their line and continuum emission, and (b) map H₂, H₂O, and C and O fine structure line emission in protoplanetary disks, providing a spectrum like the one shown in panel (c) at each of many spatial locations. The spectrum in (c) is based on ISO observations of a Class 0 protostar.¹⁰

As illustrated in Figure 1, SPIRIT will provide the sub-arcsecond angular resolution needed to resolve protostellar disks and planetary systems during their formative stages. SPIRIT will be used to image hundreds of these objects in the nearby regions of low-mass star formation Taurus, ρ Oph, and Perseus. Such observations will permit us to calibrate the effects of variable viewing geometry and, effectively, to finely time-resolve the development stages of a protoplanetary disk. SPIRIT will provide emission line maps in the most easily excited H_2 rotational transition at 28 μm , complementing spatially-matched JWST observations of the 17 μm line, and obviating our dependence on traditional but notoriously unreliable surrogate tracers of gas density. To summarize, SPIRIT will be able to map the distribution of dust continuum and gas spectral line emission in protostars and protoplanetary disks to fill an information void, constrain theoretical models, and greatly improve our understanding of the planet formation process.

2.1.2. Goal 2: Observe debris disks to characterize extrasolar planetary systems

The orbits followed by dust grains in established planetary systems are perturbed gravitationally by the planets. Orbital resonances produce dust concentrations,^{11, 12} which have been observed at visible¹³ and infrared¹⁴ wavelengths. The locations, masses and orbits of unseen planets can be deduced from the shapes and temporal variations in the dust debris disks,¹¹ just as new Saturnian moons have been found after ring gaps and features divulged their hiding places. Interplanetary dust glows brightly in the far-IR, and stars are relatively faint in this region of the spectrum, so spatially resolved IR images of debris disks will unambiguously reveal hidden planets, and will do so without the observational selection biases associated with motion-dependent (astrometric or Doppler) techniques.

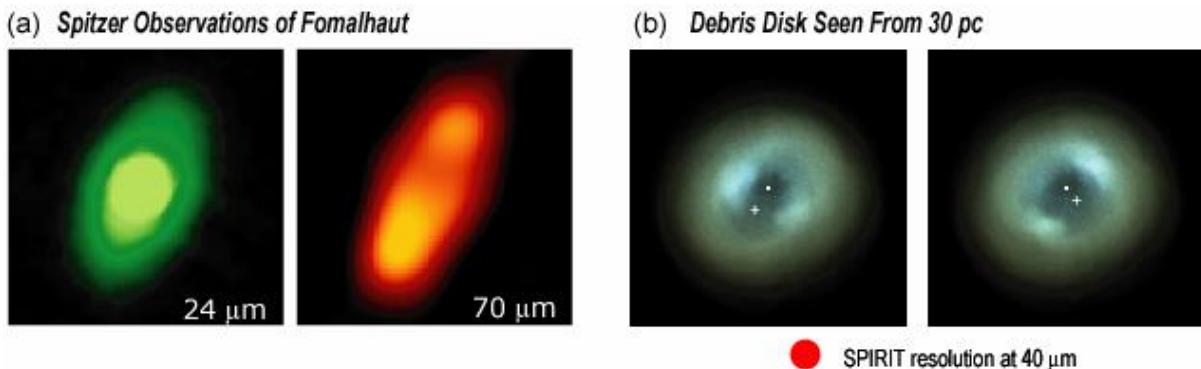


Figure 2 –The Spitzer Space Telescope is able to resolve four nearby debris disks, including Fomalhaut, shown here (a) at 24 and 70 μm (NASA/JPL-Caltech/K. Stapelfeldt). With angular resolution a hundred-fold better than that of Spitzer, SPIRIT will image with comparable clarity debris disks located half a kiloparsec from the Sun. More importantly, SPIRIT will provide clear images of a large statistical sample of debris disks, enabling discoveries of new planets and a great improvement in our understanding of the factors that influence the evolution of planetary systems. The effects of a planet on the distribution of dust in a debris disk are evident in the model shown in (b) (M. Kuchner/Princeton). The model is based on Epsilon Eri, but it is shown scaled to a distance of 30 pc to illustrate SPIRIT's resolving potential. The model images (b) show the predicted infrared emission at 40, 60, and 100 μm wavelengths color-coded as blue, green, and red, respectively. The planet (+) is shown at two orbital phases, and the resonantly trapped dust grains can be seen to have moved.

The IR imaging technique works optimally when the instrument angular resolution is well matched to the debris feature size and the wavelength observed is close to that of the spectral peak in the dust emission. Depending on the stellar spectrum, the distance of the dust grains from the star, and the grain optical properties, the emission will peak in the spectral range $\sim 20 - 60 \mu m$. More massive planets leave more prominent signatures in debris disks, but the Earth is trailed by a dust concentration,¹⁵ so the possibility exists that even so-called “terrestrial” planets can be found in IR images of debris disks. We should aim to detect features as small as 0.3 AU in diameter. Although the nearest debris disks are only a few parsecs away, an important objective is to understand our own solar system in the context of the zoo of possible planetary systems, so it will be necessary to image debris disks in a heliocentric sphere containing hundreds

of interesting objects. To that end, we should strive to image debris disks out to \sim 30 pc, at which distance 0.3 AU subtends an angle of 10 milli-arcseconds.

How does this compare with the measurement capabilities of existing and planned instruments? At 25 μ m, the resolution of JWST will be about 1 arcsecond. An interferometric baseline of 260 m would be required to provide the desired 10 mas resolution, and this is well within the capabilities of an imaging interferometer like SPECS.^{3,4} As noted in Section 1, SPIRIT represents an important step toward SPECS. SPIRIT will provide approximately ten times better angular resolution than JWST at 25 μ m, and its capability to image debris disks will be vastly superior to that of Spitzer, which can resolve only four nearby disks (Figure 2). Despite its modest angular resolution, Spitzer is revolutionizing debris disk research and teaching us that dust replenishment in evolved planetary systems may be sporadic.¹⁶ As described in the previous section, however, a lack of imaging capability has permitted degeneracy in possible interpretations to go unchecked. SPIRIT will image a large sample of debris disks to break that degeneracy, and will have the potential to reveal the presence of terrestrial planets in orbit around nearby stars. Later, SPECS will see the debris signatures of a large number of low-mass planets.

2.1.3. Goal 3: Learn how galaxies form and evolve

Mergers and interactions between protogalaxies are believed to have played a major role in the morphological development of galaxies and their star forming histories. Evidence accumulated over the past decade convinces us that observations in the far-IR are critical to our understanding of the galaxy-building process. Our own Milky Way galaxy emits half of its light in the UV/visible, and the other half at far-IR wavelengths. Indeed, except for the microwave relic radiation from the Big Bang, the entire Universe shows a similar energy balance between long and short-wavelength emission,¹⁷ reflecting the dominant status of astrophysical processes that occur on a galactic scale. Star formation and the violent activity taking place near the super-massive black holes in galactic nuclei are the most important processes.

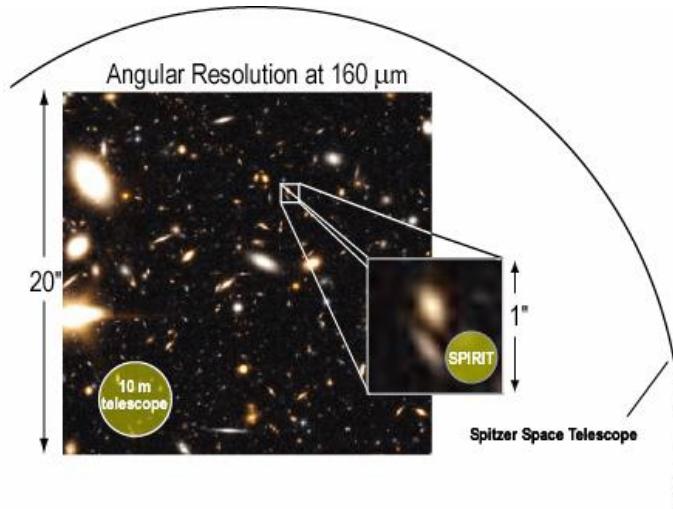


Figure 3 – A simulated JWST deep field observation (A. Benson/STScI) is used to illustrate SPIRIT’s ability to distinguish the emissions of individual high- z objects. For comparison, the Spitzer Space Telescope resolution at 160 μ m is coarser than the entire 20 arcsecond field shown, and even a 10 m diameter Single Aperture Far-IR (SAFIR) telescope would see multiple objects per beam at this wavelength.

The lack of access to far-IR measurements with high angular resolution and moderate spectral resolution has become a major hindrance to our progress in understanding these processes and their relationship to the development of galactic structure in the Universe. The most luminous objects are hidden by dust, and we would like to know if they are powered by mergers. Galaxy mergers compress and shock the interstellar medium, and trigger bursts of star formation,¹⁸ but inherent to this mechanism is its occurrence in dense, dust-laden clouds, which prevent the escape of stellar UV/visible photons. Most of the short-wavelength radiation is absorbed locally, where it warms interstellar dust to a temperature at which it glows most brightly in the far-IR. Similarly, galactic nuclear sources are often obscured from view at short wavelengths, but they heat the surrounding interstellar medium and produce strong far-IR emission. The IR spectral fingerprints of stellar nurseries and Active Galactic Nuclei (AGN) are readily distinguishable. For example, the line ratios from a triad of neon fine-structure lines unambiguously differentiates between these emission mechanisms.¹⁹ The past decade has taught us that, for reasons still poorly understood, many young galaxies and protogalaxies have IR-dominated spectra, and some have no optical counterparts whatsoever.²⁰ Clearly, to understand galaxy formation, it will

be imperative to decipher the far-IR light that reaches our telescopes. As is generally true, a variety of plausible theoretical interpretations are possible when only a spectrum or a monochromatic image is available, or when only a small number of objects are observed. The deciphering will require: (a) observations of many galaxies to sample a variety of galaxy types and evolutionary phases, (b) spectral resolution sufficient to detect the important diagnostic and interstellar gas cooling lines from ions, atoms, and molecules, (c) angular resolution sufficient to resolve many nearby galaxies into discrete regions of star formation and nuclear regions, and to see high-redshift galaxies without source confusion, and (d) broad wavelength coverage and adequate sensitivity to see galaxies at redshift $z = 3$ or greater, as much of the galaxy-building seems to have taken place since the corresponding period in the history of the Universe. Specifically, we need the equivalent of integral field spectroscopy with spectral resolution $R = 3000$, sub-arcsecond angular resolution, wavelength coverage from $\sim 25 \mu\text{m}$ to $\sim 100(1+z) = 400 \mu\text{m}$, a field of view ~ 1 arcminute in diameter, and sensitivity to emission at the micro-Jansky per beam level. ALMA will extend these capabilities by measuring the SED peak in galaxies at $z > 3$.

Unlike Spitzer, Herschel, SOFIA, and even the 10 m SAFIR Telescope, SPIRIT will be able to observe galaxies in the far-infrared without the adverse effects of source confusion (Figure 3), and it will be able to measure the information-rich far-IR spectra of these objects (Figure 4). Thus, SPIRIT will provide critical information complementary to that accessible to JWST. Together, JWST, SPIRIT and ALMA will revolutionize our understanding of galaxy formation and the related processes of star formation and heavy element synthesis.

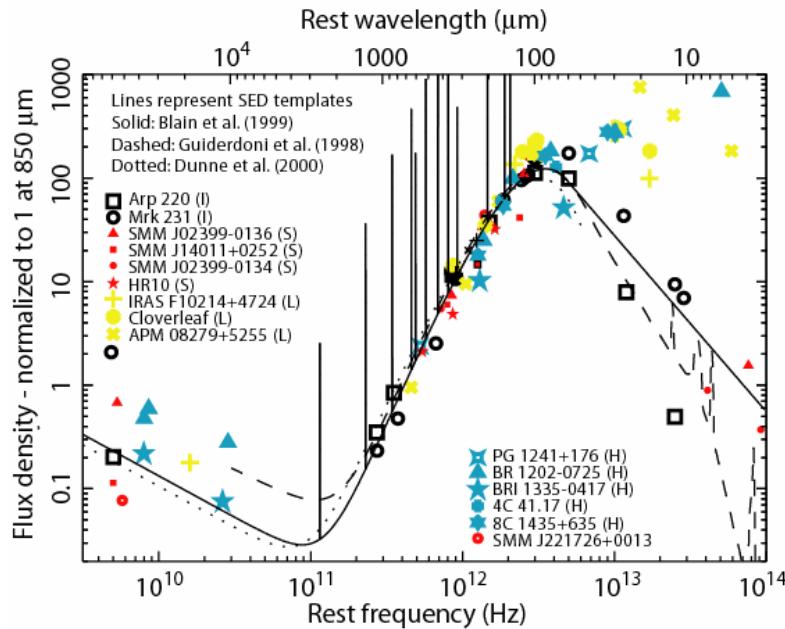


Figure 4 –The far-IR spectrum of a galaxy [19] contains a large fraction of the bolometric luminosity and many strong emission lines, which can be used to calculate physical conditions in the interstellar medium, estimate rates of star formation, and measure a galaxy's redshift. SPIRIT will be able to measure the line intensities and the far-IR spectral energy distributions of galaxies out to high redshifts to probe the epoch of most-intense star formation ($z \sim 2 - 3$), distinguish between nuclear and non-nuclear emission, and determine the relationship between galaxy mergers and star formation activity.

2.2. Additional possible scientific applications for SPIRIT

We envision that Guest Observers will use SPIRIT to address a wide range of interesting astrophysical questions. As part of its science goal prioritization process, the SPIRIT Science Team considered many possible applications for a far-IR interferometer in addition to the three primary objectives described above. The following set of applications illustrates the potential of a SPIRIT mission to solve a variety of astrophysical problems: (1) Test the unification model for AGN by measuring the physical conditions in the tori surrounding the nuclei of nearby galaxies; (2) Measure the spectra of extrasolar gas giant planets to determine their effective temperatures and assess their chemical diversity; (3) Map nearby spiral galaxies in fine structure and molecular lines to better understand the role of large-scale gas compression in the process of star formation; (4) Measure the temperature and mass structures in "starless cores" and infrared-dark clouds to study the earliest stages of star formation; and (5) Follow up Spitzer observations of Kuiper Belt and other cold objects in the solar system to mine the fossil record of planetary system formation.

3. SPIRIT MISSION CONCEPT

From the scientific objectives described in Section 2, the following measurement requirements were derived and adopted for the SPIRIT C Design: SPIRIT will cover the wavelength range 25 to 400 μm ; the angular resolution will be 0.3 arcseconds at 100 μm and scale in proportion to the wavelength; the spectral resolution will be 3000; the instantaneous field of view (FOV) will be 1 arcminute; and the field of regard will be 40 degrees wide and centered on the ecliptic plane (at any given time during the year, SPIRIT will be able to observe a point in the sky within 20 degrees of the anti-Sun direction). In addition, we required that the micro-Jansky continuum emission and the important interstellar cooling and diagnostic spectral lines from galaxies at redshift $z \sim 3$ be detectable in a “deep field” exposure lasting approximately two weeks.

A typical SPIRIT observation will take about 1 day and yield, after ground data processing, a “data cube” with two high-resolution spatial dimensions and a third, spectral dimension. The data can be explored either as a sequence of images, each of which shows the appearance of the target field at a discrete wavelength, or as a set of spectra, one for each position in the FOV. At each field position, or for a set of discrete objects in the field, SPIRIT will measure a chemical fingerprint and indicators of physical conditions, such as gas and dust temperature and density, enabling astronomers to achieve the objectives outlined above.

A single scientific instrument will provide the required measurement capabilities. SPIRIT has two 1-m diameter light-collecting telescopes and a central beam-combiner attached to a rigid boom. The telescopes are mounted on trolleys, which move along rails to provide interferometric baselines ranging in length from 6 m to 36 m. The boom rotates during an observation with the rotation axis pointing toward the target field. The resulting spatial frequency “u-v plane” coverage can be tailored according to the expected spatial brightness structure in the scene and can be dense, so SPIRIT will produce very good images. For each baseline observed, an optical delay line is scanned, yielding a set of white light interferograms, one for each pixel in SPIRIT’s four pairs of detector arrays. SPIRIT is a “double Fourier” interferometer^{21 - 24} because spectral information is available in these interferograms; the delay line is scanned through the distance required to (a) equalize path lengths through the two arms of the interferometer for all angles in a 1 arcmin wide FOV, and (b) provide spectral resolution $R = 3000$.

While all of the essential elements of mission design were addressed during the SPIRIT study, below we describe only the novel aspects of the optical, cryo-thermal, detector, metrology, and mechanism subsystems, and the SPIRIT operations concept.

3.1. Optical system design

SPIRIT’s light-collecting telescopes sample two sections of an incident wavefront and direct compressed, collimated beams into a beam-combining instrument. An off-axis telescope design (Figure 5) was chosen to avoid wavelength-dependent diffraction effects which would complicate calibration and compromise the sensitivity to fringe visibility. The telescopes compress the beam by a factor of 10 to minimize the total optical surface area, and therefore the thermal mass that must be cryo-cooled to meet the sensitivity requirement. Compression at the collector telescopes by more than the optimal ratio magnifies off-axis field angles and increases the size of the mirror required to intercept the beam at the beam combiner. Compression by less than the optimal ratio requires a large tertiary mirror at the collector telescope, which is both harder to cool and harder to steer to maintain alignment with the beam combiner optics.

SPIRIT has a Michelson (pupil plane) beam combiner. This type of instrument permits the use of a smaller number of detector pixels and has relaxed alignment tolerances compared with the alternative Fizeau design, and the Michelson technique naturally enables Fourier Transform Spectroscopy. To develop the technique of wide field-of-view double Fourier interferometry we built the Wide-field Imaging Interferometry Testbed (WIIT),²² which is essentially a scale model of SPIRIT. Our experience with WIIT²³ informed our design choices, and our newly-developed optical system model of the testbed²⁴ will ultimately serve as the basis for a high-fidelity model of SPIRIT.

As illustrated in Figure 6, light incident upon the SPIRIT beam combiner is further compressed with off-axis optics, recollimated, split into four wavelength bands with wire mesh dichroics to optimize optical system and detector performance, directed through optical delay lines up to the point of beam combination at a wire mesh 50/50 beamsplitter,

and focused with off-axis reflectors onto detector arrays. An opto-mechanism in one collimated beam (“PCM” in Figure 6) provides pathlength correction with control feedback from an internal metrology system. The other collimated beam passes through a scanning optical delay line. In each wavelength band, both Michelson output ports are used, so there is no wasted light and the design is robust against a detector failure. The optical design is symmetric; the light collected at one telescope is reflected by mirrors and reflected or transmitted by dichroics identical in design to the optical elements encountered by light from the other telescope. This symmetric arrangement balances the throughput, simplifies calibration, and minimizes instrumental visibility loss.

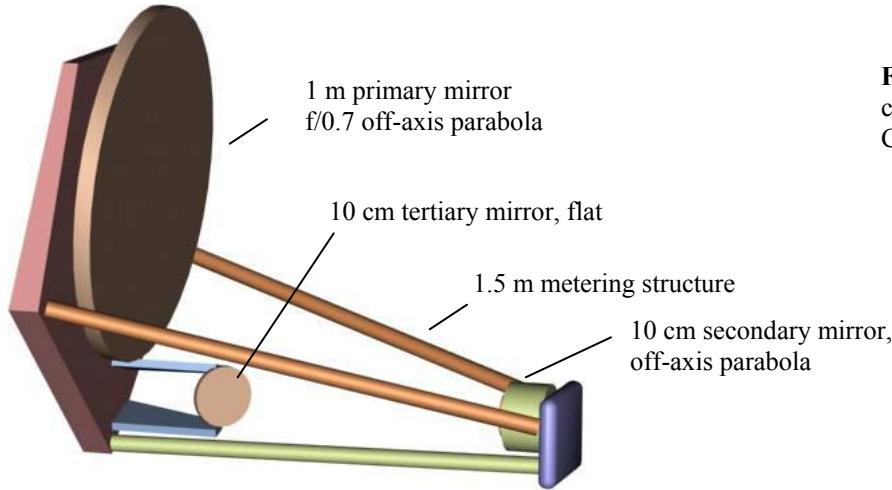


Figure 5 – The SPIRIT light collectors are off-axis, afocal Cassegrain telescopes.

The optical elements have no extraordinary fabrication or material requirements. Surface roughness and mid-spatial frequency tolerances are such that some of the customary polishing steps may be avoided. Aluminum, silicon carbide, composite, and beryllium are all acceptable materials, and aluminum was adopted in the C design. The capability exists in the US and the UK to produce “designer” dichroics and beamsplitters with wavelength-dependent transmission and reflection curves which approach the ideal rectangular shapes.

3.2. Thermal design and cryocoolers

SPIRIT’s thermal performance is crucial to its ability to satisfy the sensitivity requirements. Instrumental noise, either stray thermal radiation or detector noise, must not exceed the photon noise from the sky. Thus, the optics must be cooled to 4 K. We developed a thermal model and gave careful thought to thermal system design and stray light baffling. We modeled the radiative, conductive, and mechanism-generated parasitic heat loads from all sources, and used conservative estimates and large margins for the relatively poorly known terms in the thermal model. Many features of the SPIRIT design, such as low-conductivity structures and tailored multi-layer sun shades and shields, were optimized to satisfy thermal system performance requirements. The result is a system whose cooling requirements can be met with cryocoolers only modestly enhanced relative to those currently under development for JWST under NASA’s Advanced Cryocooler Technology Development Program (ACTDP). A subscale engineering testbed designed to validate the SPIRIT and related thermal models is under development, and a space validation experiment is under consideration for the New Millennium mission ST-9.²⁵

The advantages of cryocoolers over cryostats are manifold. Elimination of a mission lifetime-limiting expendable in favor of a device whose design lifetime can easily surpass the desired mission duration is an obvious plus. In a mission like SPIRIT, where the scientific performance, especially angular resolution, is limited by the fairing dimensions in available, affordable launch vehicles, the vastly reduced volume of a cryocooler relative to a cryostat of equivalent cooling capacity is a tremendous advantage. Cryocoolers are also much less massive than cryostats and their associated support structures, a factor which can also lead to lower launch cost. Dewars also introduce unique Integration & Test (I&T) and launch operations challenges which can be avoided if cryocoolers are used.

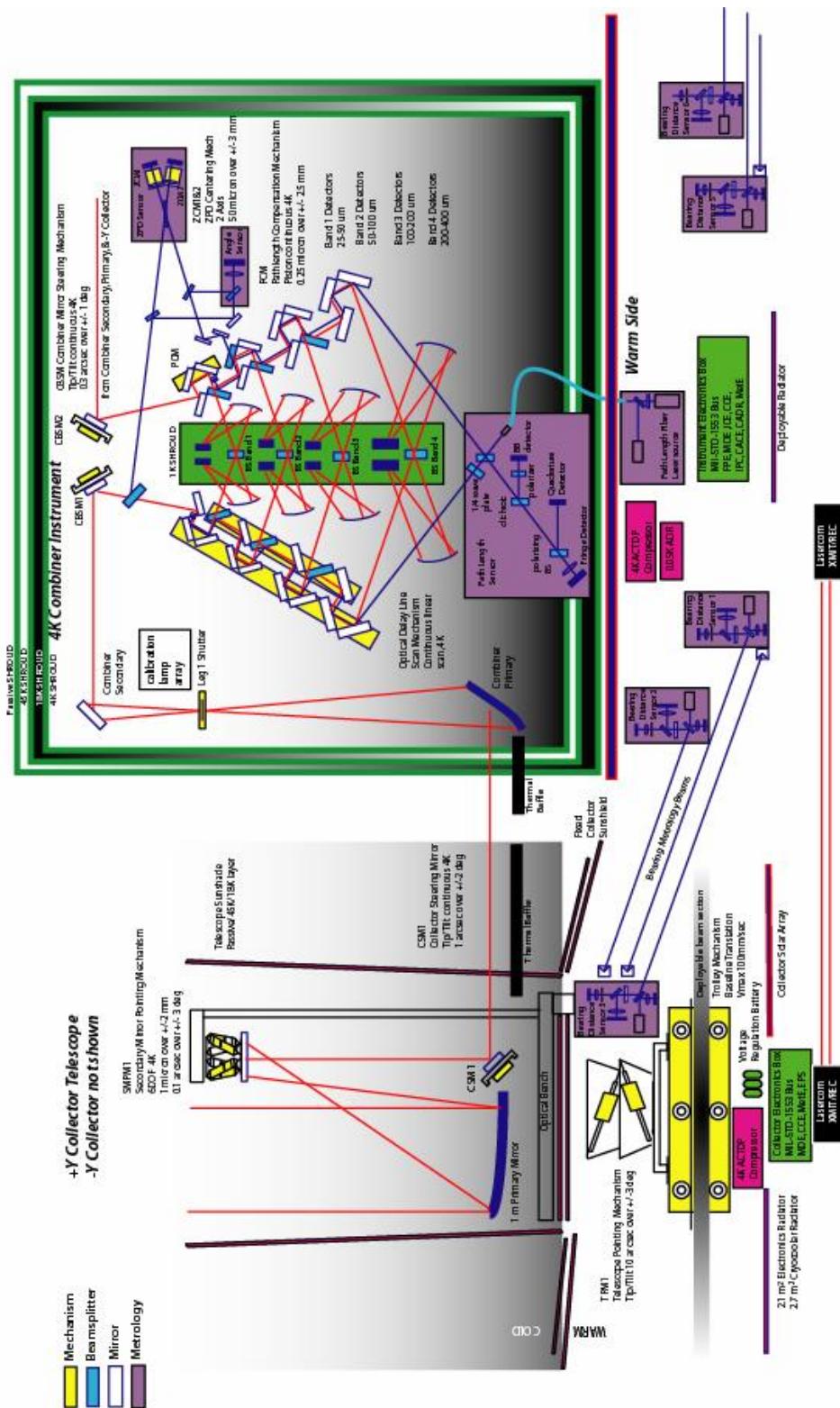


Figure 6 – Schematic diagram showing major SPIRIT instrument components. Only one light-collecting telescope is shown.

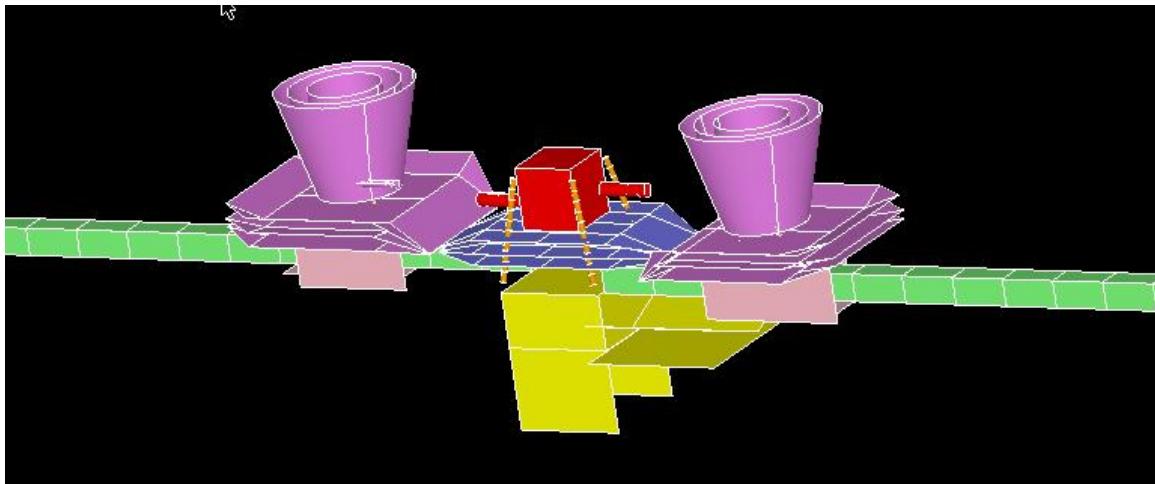


Figure 7 – SPIRIT’s shades and shields provide passive cooling, prevent stray thermal radiation from reaching the focal plane, use space economically, and provide access to the required field of regard. The radiators located far below the centrally located spacecraft are the only deployable elements of this system.

Separate ACTDP cryocoolers are provided for each of SPIRIT’s telescopes and for the beam combiner, and each of these major observatory components has a redundant cryocooler to reduce risk. The beam combiner also contains a continuous adiabatic demagnetization refrigerator (CADR) with a 4K “warm” interface, which provides detector cooling to 50 mK.

Instead of shading the entire boom structure, we elected to shade only the components that must be actively cooled: the telescopes and the beam combiner instrument module. A boom-sized sun shade would have been at least 40 m long, challenging to deploy, and it would have unnecessarily consumed precious volume in the launch shroud. The SPIRIT multi-layer shades (Figure 7) are sized and shaped to protect cold components, including inner shade layers, from sunlight (at angles up to 20 degrees from the anti-Sun direction) and thermal radiation sources on the observatory. The telescope shades move along the boom with the telescopes. The beam combiner shade shields the instrument from the warm spacecraft. Additional shields and baffles enclose the telescopes and contribute to passive cooling and the elimination of stray thermal radiation.

3.3. Detectors

The design attributes described in Section 3.2 will limit the undesirable radiation reaching SPIRIT’s detectors to a small fraction of the celestial light intensity from the targeted region. Additionally, to meet the SPIRIT sensitivity requirement, the detector noise must contribute negligibly (<10%) to the output signal. Upper limits to the tolerable detector Noise Equivalent Power (NEP) were derived for SPIRIT from the accurate COBE absolute sky brightness measurements. The detector NEP must not exceed $1.9, 1.1, 0.7, \text{ or } 1.8 \times 10^{-19} \text{ W Hz}^{-1/2}$ in the $25 - 50, 50 - 100, 100 - 200, \text{ and } 200 - 400 \mu\text{m}$ wavelength bands, respectively.

Each of the four SPIRIT wavelength bands has its own dedicated set of detector arrays. We employ the spatial multiplexing technique being developed at GSFC under the NASA ROSES/APRA-funded “Wide-field Imaging Interferometry” study,^{22, 23} in which adjacent detector pixels record Michelson interferometric fringes from contiguous regions of the sky to cover the desired field of view. In the SPIRIT C design, the detector pixels Nyquist sample the Airy disk of a 1 m telescope at the geometric mean wavelength in each of the four octave-wide wavelength bands. Accordingly, the detector array for the shortest wavelength channel has 14×14 pixels, and the arrays for each successively longer wavelength channel contain $7 \times 7, 4 \times 4, \text{ and } 2 \times 2$ pixels. Additional experimentation and analysis are needed to determine if sparser-than-Nyquist sampling is preferable, in which case the pixel count could be slightly reduced. The modest number of detector pixels and the high observing efficiency achievable when detector arrays are used instead of observatory pointing to cover the field of view are important features of the SPIRIT design.

From the requirement that SPIRIT be capable of densely sampling the u-v plane and providing $R = 3000$ spectroscopy over a 1 arcminute FOV in 1 day we derived the optical modulation rate resulting from a scan of the delay line and the corresponding detector time constant. The detector time constant must not exceed 185 μ s.

Transition-Edge Sensor (TES) bolometers cooled to 30 mK, with SQUID amplifiers for readout, are theoretically capable of satisfying the SPIRIT detector noise and speed requirements, and recent lab work has yielded promising results.^{26, 27, 28}

3.4. Metrology

To minimize instrumental degradation of the fringe visibility, light from both arms of a Michelson interferometer must arrive at the combination plane with a large fractional beam overlap and a small angular wavefront misalignment (specifically, misalignment by no more than a small fraction of a wavelength across the pupil plane). We required an uncalibrated visibility of 0.94 on an unresolved reference source. In other words, the visibility loss due to all instrument imperfections, including optical surface imperfections, totals less than 6%.

An internal metrology system provides the information needed to maintain pointing and optical system alignment and stabilize the optical path length, and it provides knowledge of the baseline length and the time-varying optical path difference between the two arms of the interferometer during delay line scans. To accomplish these objectives, the metrology system directly measures certain dimensions of the opto-mechanical hardware, including the separations and relative orientations of mirrors in the light collecting telescopes and the beam combiner, and the separations between path length controlling mirrors inside the beam combiner, as shown schematically in Figure 6.

Guide stars are used to orient the spacecraft in absolute coordinates, and near-IR point sources in the science field of view serve as phase references for the optical path external to the instrument.

The metrology and control tolerances for SPIRIT are greatly relaxed relative to those for interferometers designed to operate at shorter wavelengths or null starlight, such as the Space Interferometry Mission (SIM) and Terrestrial Planet Finder (TPF). We assigned visibility loss tolerances to various instrument subsystems and derived subsystem requirements and descriptions of the metrology hardware components (path-length sensor, angle sensor, zero-path-difference sensor, laser ranging, and tip/tilt sensors) depicted in Figure 6. Some of the SPIRIT hardware is common to SIM, and we concluded that a modest investment in metrology technology development can lead to significantly lower total cost if advantage is taken of the more easily satisfied SPIRIT requirements.

3.5. Mechanisms

The mechanisms in SPIRIT are shown in Figure 6. Beam steering and path length control mechanisms provide a stable optical bench. At each telescope, a focusing mechanism adjusts the position of the secondary mirror, tip and tilt adjustments enable telescope pointing, and a trolley mechanism enables telescope movement to an arbitrary position along the boom to adjust the baseline length. A shutter mechanism equipped with an array of calibration lamps is located after the first optic in the beam combiner and can be used to calibrate the detector performance or operate the interferometer in “single-dish” mode to obtain low spatial frequency information. The optical delay line (ODL) scan mechanism provides linear motion and operates almost continuously throughout the mission. Relevant spaceflight heritage exists for many of SPIRIT’s mechanisms, including the ODL scan mechanism.

Many of the mechanisms operate at 4 K. The parasitic heat loads from these cryogenic mechanisms will be limited so as not to exceed the capacity of the cryocoolers to remove heat from the system. The actuators in these mechanisms will take advantage of the low-temperature environment and rely on superconductivity to keep Ohmic losses to a minimum.

3.6. Deployment and operation

The preferred location for SPIRIT is the Sun-Earth Lagrange point L2, which offers deep radiative cooling and minimum interference from the Earth and Moon, while requiring only a single-sided sunshield. Delta IV and Atlas V launch vehicles were considered, and the latter was chosen due to its larger fairing dimensions and adequate lift capacity. The

fairing volume limits the boom length and therefore the achievable angular resolution of the interferometer. Figure 8 shows SPIRIT in its stowed and fully-deployed configurations.

We developed a detailed description of the mechanical system, with a parts and mass properties inventory, and conducted structural analyses of SPIRIT in the launch and deployed configurations. Our structural analysis covered both dynamics and thermal distortion.

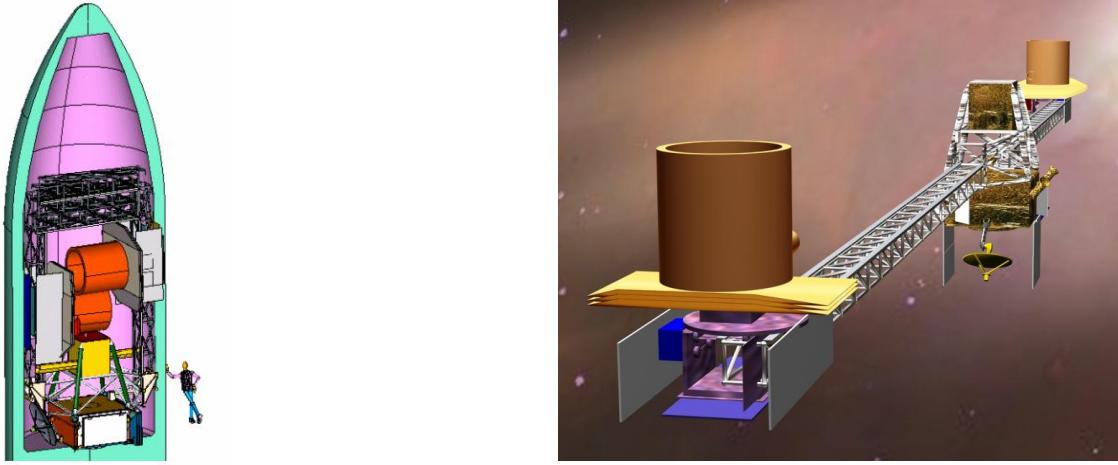


Figure 8 – SPIRIT and its expendable launch support structure, when stowed for launch (left), are 8.7 m tall and were designed to fit into an Atlas V 5-medium fairing. The deployed observatory is shown in an artist's concept (right).

Four or more mid-course correction maneuvers are made prior to L2 insertion in the 15th week after launch, and the major post-launch mission phases are as follows:

- Deployment and spacecraft checkout phase (8 days) – deploy expendable launch support structure and solar arrays, acquire Sun, deploy high-gain antenna, check out spacecraft subsystems (e.g., communications, attitude control, thrusters), deploy radiator, boom, and telescope transport trolleys;
- Instrument warm checkout and cool-down phase (weeks 2 – 5) – activate cryocoolers and check out each subsystem as soon as its temperature permits;
- Instrument cold checkout and science commissioning phase (weeks 6 – 12) – align and calibrate the instrument with real-time ground contact, and verify performance;
- Normal operations phase (subsequent 3 – 5 years) – gather data on selected targets; station-keeping maneuvers about four times per year;
- Decommissioning at the end of the mission phase – propel the spacecraft away from L2.

SPIRIT will operate for at least 3 years (5-year goal) in a large-amplitude Lissajous orbit around Sun-Earth L2. The instantaneous field of regard is limited by the size of the sun shades to a +/-20 deg cone around the anti-Sun direction. Over the course of a year, SPIRIT will have a 40-degree wide viewing zone around the ecliptic plane. The science targets available in that zone (Figure 9) will enable us to fulfill the science objectives of the mission.

An observation sequence comprises a slew to the target field, target acquisition (including lock on angle and ZPD tracking), and science data acquisition (scan delay line and rotate the boom all the time; calibrate detectors; adjust telescope positions to sample a new baseline length after every half-rotation at specified time intervals until all of the desired baselines are measured). A typical observation will take about 28.2 hours, with 2 hours allocated for slew and settle, one hour for trolley movements, 24 hours for collecting science data, and 1.2 hours for data downlink. The observing efficiency is 85% in this case, and will be even higher for deep exposures, which could last up to $\sim 10^6$ seconds (i.e., 11 days, instead of the typical 1-day exposure time). SPIRIT will yield approximately 400 Gbits of data per day.

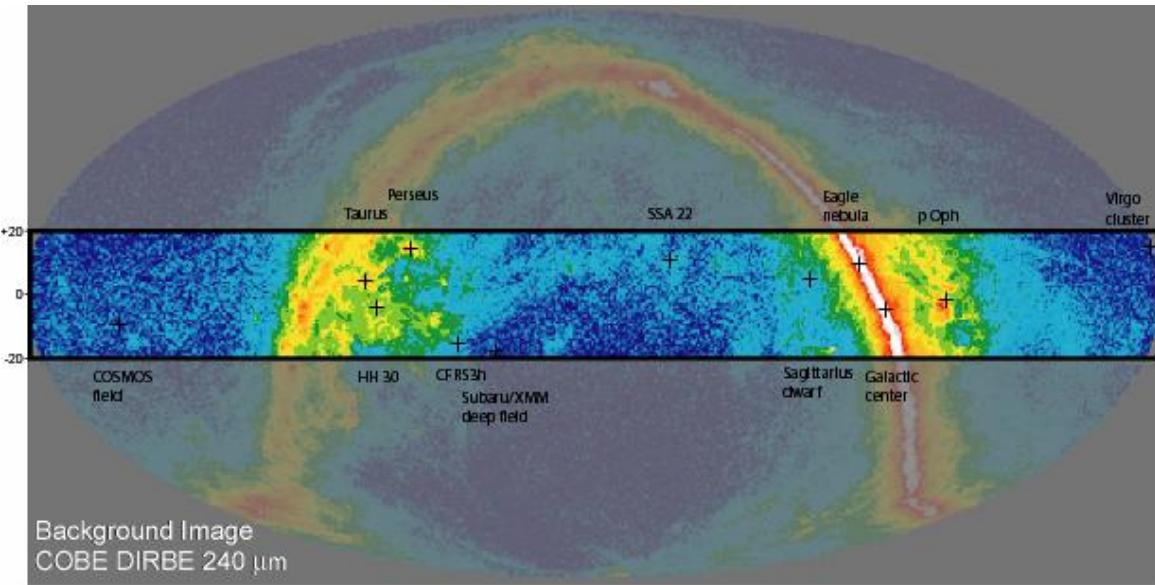


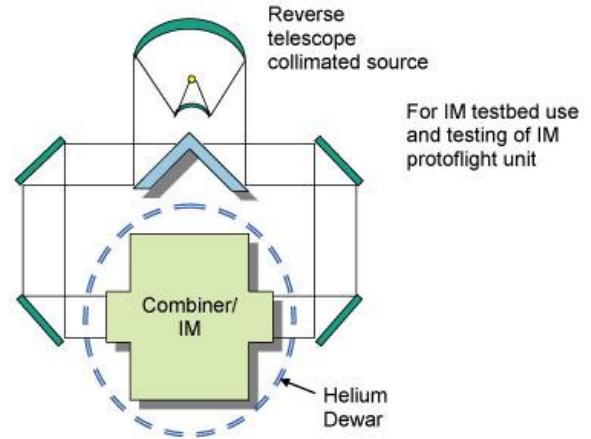
Figure 9 – SPIRIT will have a view of the sky that permits access to all of the relevant object types, from Galactic star forming regions (e.g., Taurus and ρ Oph) to extragalactic “deep fields” (e.g., the COSMOS field and SSA 22). The titles in this figure correspond to the + symbols which lie above or below them and indicate the object positions.

SPIRIT has only one mode of operation, the double Fourier mode, but has the flexibility to observe a wide variety of astronomical sources with optimal science productivity. Operational parameters will be selectable by the observer, who will specify the desired spectral resolution (affects delay line scan range), field of view (affects number of pixels to read and, to a small extent, the delay line scan range), sensitivity (affects total observation time), and angular response function, or “synthesized beam” shape (affects the time spent at each interferometric baseline). This flexibility comes at a small price, primarily impacting the flight software. Observations can be queue-scheduled, giving mission operators the opportunity to optimize the sequence of target visits, and the parameter settings for each observation can be uplinked months in advance.

3.7. Integration and test (I&T) plan

Several aspects of the recommended I&T program are worth noting here, as they indicate how risks can be reduced to tolerable levels at an acceptable cost. In particular, we advocate: (a) incorporation of lessons from major missions currently in the formulation phase, such as JWST and SIM; (b) early development of a SPIRIT I&T Plan, and early consideration of test facility limitations, including their physical dimensions and geographic locations, which can affect the design and the costs and risks associated with shipping and handling flight hardware; (c) utilization of existing test facilities; (d) a “protoflight” approach which avoids unnecessary hardware replication and test repetition and seamlessly flows from component technology validation to engineering test units, and ultimately to a flight-qualified, fully-integrated instrument; and (e) to the extent possible, the light collecting telescopes and the beam combining instrument module should be developed and tested in parallel, ground support equipment (GSE) should be reused, and facility use should be optimally scheduled. The instrument module is sufficiently compact that it can be performance tested independently of the light collecting telescopes, as shown in Figure 10. The SPIRIT I&T plan outlines all the steps believed to be necessary to integrate, characterize, calibrate, and test the complete instrument functionally, for performance, and environmentally, using existing facilities.

Figure 10 – The beam combining instrument fits into existing thermal vacuum chambers and can be tested independently of the light collecting telescopes. The telescopes simply collect light and steer a collimated beam toward the beam combiner, so they can be tested individually in a similar manner.



4. MEASUREMENT CAPABILITIES COMPARED WITH THOSE OF OTHER FACILITIES

Ultimately, SPIRIT's ability to solve otherwise unsolvable fundamental scientific problems, rather than its unique measurement capabilities, make the mission compelling, but a straight comparison of measurement capabilities can also be informative. In Figures 11 and 12, respectively, we show the angular resolution and sensitivity of SPIRIT as a function of wavelength, and compare SPIRIT with current, near-term, and “vision” missions for the far-IR, and with JWST, which operates at shorter wavelengths, and ALMA, which operates at longer wavelengths.

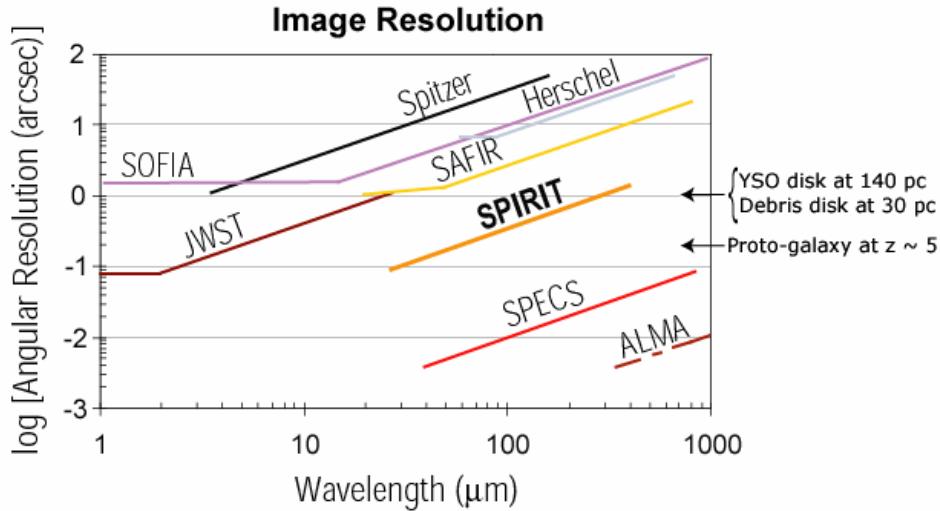


Figure 11 – Angular resolution available with current, next-generation, and future infrared and submillimeter observatories. SPIRIT will provide one hundred times better angular resolution than the Spitzer Space Telescope. The resolution is comparable to that of JWST, but at ten times longer wavelengths.

Figure 11 shows that SPIRIT will bridge a gap in imaging capability between the longest wavelengths accessible to JWST and the shortest wavelengths accessible to ALMA. The canyon that needs to be spanned is several orders of magnitude deep and stretches across four octaves in wavelength.

Line Sensitivity of Future IR/Sub-mm Telescopes

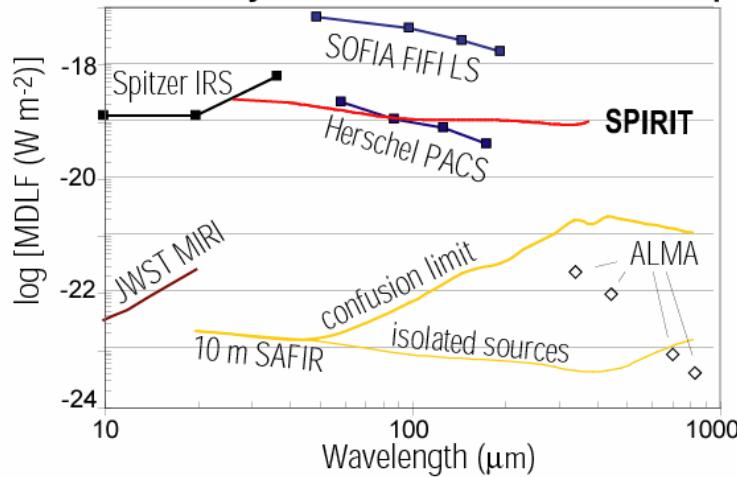


Figure 12 – Minimum Detectable Line Flux (MDLF) available with current, next-generation, and future infrared and submillimeter observatories. SPIRIT will approximately match the Spitzer IRS sensitivity, but at higher spectral resolution and much higher angular resolution. SPIRIT has less light collecting area than SOFIA and Herschel, but SPIRIT’s modest aperture area is compensated by cryogenically cooled optics. Quoted values are for a 10^5 sec exposure, except 10^4 sec for SOFIA.

According to Wien’s Law, the temperatures of objects that glow most brightly between 25 and 400 μm are 116 to 7 K. Only the darkest interiors of starless molecular clouds could be colder than 7 K and have their peak emission at submillimeter wavelengths, and many of the interesting objects warmer than 116 K are concealed by dust and unobservable at UV and visible wavelengths. JWST will be very sensitive to redshifted starlight and the warm emission in protostellar and protoplanetary objects. ALMA will be sensitive to cold interstellar and interplanetary material, but it will measure the continuum of all but the highest redshift objects in the Rayleigh-Jeans tail, with poor temperature sensitivity and image contrast. SPIRIT will observe these objects where they emit the bulk of their radiation, and with angular resolution comparable to or better than that of JWST, depending on the wavelength of interest. With JWST, SPIRIT, and ALMA working in tandem, the astronomical community will have an extremely powerful arsenal of observing tools.

Figures 11 and 12 only partially illustrate the new discovery space that SPIRIT will open to exploration. To fully appreciate the enhancement in measurement capability, one must also recognize that, although SPIRIT’s sensitivity will be comparable to that of Spitzer, SPIRIT provides this sensitivity with $R = 3000$ spectral resolution in the spectral range $25 < \lambda < 400 \mu\text{m}$, whereas the Spitzer Infrared Spectrograph (IRS), the only spectroscopic instrument on the telescope, provides $R = 600$, and only at wavelengths $\lambda < 37 \mu\text{m}$. Spectral dilution at $R = 3000$ is not severe, and even relatively weak lines will be detectable with SPIRIT. Indeed, at $R = 3000$, SPIRIT will be able to measure the kinematics of merging protogalactic objects at high redshifts. Many of the spectral lines accessible to SPIRIT are astrophysically significant as probes of physical conditions or diagnostic tools. For example, the rotational and rovibrational lines of H_2O , CO and small hydrides probe temperatures, densities, and isotope abundances in molecular clouds and protostellar disks; the far-UV field strength, temperature and density in “photon-dominated” regions can be measured with observations of the fine-structure lines of C^+ at 158 μm , the neutral oxygen lines at 63 and 145 μm , and the neutral carbon lines at 370 and 609 μm ; and the $[\text{Ne V}] (14.24 \mu\text{m})/[\text{Ne III}] (15 \mu\text{m})$ line ratio measures the ionization parameter in Active Galactic Nuclei (AGN).

5. SUMMARY

The Space Infrared Interferometric Telescope (SPIRIT) was selected for study by NASA as a candidate Origins Probe mission. SPIRIT is a two-telescope Michelson interferometer operating over a nominal wavelength range 25 to 400 μm and offering a powerful combination of spectroscopy ($\lambda/\Delta\lambda \sim 3000$) and sub-arcsecond angular resolution imaging in a single instrument. With angular resolution two orders of magnitude better than that of the Spitzer Space Telescope, and with comparable sensitivity, SPIRIT will enable us to learn how planetary systems form in protostellar disks, how they acquire their chemical structure, and how they evolve, and it will enable us to learn how galaxies formed and evolved

over time. SPIRIT could be ready to launch a decade from the time a significant investment is made in the key enabling technologies, particularly detectors, cryocoolers, and cryogenic mechanisms.

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